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Smart Grid Control and Communication: the SmartC2net Real-Time HIL Approach

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Abstract—The expected growth in distributed generation will significantly affect the operation and control of today's distribution grids. Being confronted with fast fluctuating power from distributed generations, the assurance of a reliable service (grid stability, avoidance of energy losses) and the quality of the power may become costly. In this light, Smart Grids may provide an answer towards a more active and efficient electrical network. The EU project SmartC2Net aims to enable smart grid operations over imperfect, heterogeneous general purpose networks, which poses a significant challenge to the reliability due to the stochastic behaviour found in such networks. Therefore, key concepts are presented in this paper targeting the support of proper smart grid control in these network environments and its Real-Time Hardware-In-the Loop (HIL) verification. An overview on the required Information and Communication Technology (ICT) architecture and its functionality is provided and a description of a relevant use case that deals with voltage control on medium and low voltage networks along its evaluation approach on an experimental test bed is detailed.

Index Terms — Smart Grid Control, heterogeneous communication networks, Hardware-In-the-Loop, Power HIL.

I. INTRODUCTION

Campaigns from Europe's national governments promoting green energy have led to an increased penetration of distributed Photovoltaic (PV) systems in households, especially in Germany and Southern Europe. Installation of small household wind turbines, newly supported in Denmark for example, will further increase the amount of fluctuating power in distribution grids. All these dispersed generation units can introduce power quality issues as well as bottlenecks and congestion. For example, some of the Danish Distribution System Operators (DSOs) have encountered problems with voltage profiles in feeders with high penetration of household PV installations. By adding more fluctuating power from small wind turbines, the present problems, i.e. poor voltage and power quality, will worsen, eventually triggering the disconnection of loads or entire parts of the distribution grid. In some cases power quality issues might be solved by

curtailment of power. However, this can result in energy systems devoid from clean and renewable energy sources.

Typically, DSOs monitor the Medium Voltage (MV) feeders and maintain admissible voltage levels in these feeders by means of On-Load Tap-Changers (OLTC) installed in primary substations (High Voltage to Medium Voltage). Thus, voltage on a substation's MV side is shifted upwards or downwards in small steps according to measurements at critical points. However, this control is not able to run smoothly and very often as required by the intermittent fluctuating renewable sources. Capacitor banks, also installed in primary substations, may contribute with an additional reactive power injection, hence boosting the voltage in MV feeders. However, fast transients are introduced into the grid when switching the capacitor banks on and off. Moreover, there are limitations regarding the number and the frequency of this switching imposed by technical requirements. Notwithstanding, all these control capabilities are not designed to cope with fluctuating renewable energy. The situation is more critical in secondary substations (MV to LV) where all the small dispersed generation units at household level are actually being installed. The DSOs are currently not automatically controlling the voltage profiles in these Low Voltage (LV) grids. In some cases they might only have some limited information regarding the load of these substations. Currently, renewable energy systems like small wind turbines and solar PVs are capable of providing smooth control of reactive power. However, this capability is not used in a coordinated manner by DSOs. The SmartC2Net project strives to activate these capabilities and to provide DSOs with more and better control options for heterogeneous communication networks. To ensure a reliable operation of the electrical grid with high penetration of renewable in MV/LV side while using heterogeneous networks, the SmartC2Net employs a concept of two interacting control loops [1] and [2]. As shown by Figure 1, the inner communication control loop deals with the intricacies of managing networks and their related protocols. It is thus in charge of handling the smart grid control messages, which are issued by the outer energy control loop. The energy control algorithms of this outer loop work on

The diagram illustrates the SmartC2Net architecture, which is designed for energy-efficient network management. It features a central cloud-like shape representing the network, with several key components and their interactions:

- Energy Control Algorithms:** Located at the top, it interacts with the SmartC2Net Adaption Layer via bidirectional arrows.
- SmartC2Net Adaption Layer:** Acts as a central hub, interacting with the Energy Control Algorithms, the Outer (Energy) Control Loop, the Inner (Communication) Control Loop, and the Energy Sensors Energy Actors.
- Outer (Energy) Control Loop:** Interacts with the SmartC2Net Adaption Layer and the Energy Sensors Energy Actors.
- Inner (Communication) Control Loop:** Interacts with the SmartC2Net Adaption Layer and the Network QoS Parameter Adjustment.
- Network Monitoring:** Interacts with the Inner (Communication) Control Loop and the Network QoS Parameter Adjustment.
- Network QoS Parameter Adjustment:** Interacts with the Inner (Communication) Control Loop and the Network Monitoring.
- Energy Sensors Energy Actors:** Located at the bottom, it interacts with the SmartC2Net Adaption Layer and the Outer (Energy) Control Loop.
- Accidental Faults:** Represented by a large arrow pointing into the network cloud from the left.
- Malicious Attacks:** Represented by a large arrow pointing into the network cloud from the right.
- Communication Networks:** A label indicating the scope of the network, with examples: Wireless: g LTE, Mobile WiMAX, etc.

The overall flow suggests a feedback loop where the network monitors its state, adjusts parameters, and manages energy consumption based on external control loops and sensors, all while being resilient to faults and attacks.

@SmartC2Net

The outer energy control loop performs monitoring and control tasks for the numerous distributed components of the grid. It therefore needs a means for communication enabling the reception of sensor data from field devices, as well as the transmission of control signals. Due to the different locations of grid devices, varying communication infrastructures are in place for delivering data with given protocols. As reliability is of paramount importance, the overall system needs to maintain a high level of service quality in cases of poor network performance, partial or even complete failures and cyber-attacks. In order to demonstrate and evaluate the developed ICT platform's capabilities to operate safely under challenging conditions, several real-world use cases are in focus of the SmartC2Net project [1]-[2]. Communication infrastructure solutions and middleware have become of interest in supporting such smart grids [2]. Here SmartC2Net project takes into account a unique and tight interaction between the two loops and a close link to evaluation in a Real-Time realistic setup described in this paper.

The following four use cases are considered in the SmartC2net project [3]:

- ii) External Generation Sites (EGS): focusing on meeting demand and responses at medium and low voltage grids in different communication network conditions and technologies.

- iv) Customer Energy Management Systems (CEMS) and Automated Meter Reading (AMR): focusing on the integration of devices on customer sites.

The project's second use case, External Generation Site, is concerned with decentralized energy storage and generation, aspects of Smart Grids that experience a steady rise in deployment and thus importance [3]. Despite being primarily tasked with the control of low voltage grid entities, this use case also incorporates interfaces to mid and high voltage grid parts like secondary and primary substations. The reasoning behind this can be found in the benefits substation controllers might extract from an ability to communicate with external generation sites. Examples of such profitable information exchanges are the ability to pass the flexibility aggregated on the low voltage level on to MVC, as well as the optimization of energy costs, losses and low voltage profiles. Such functionalities depend on reliable information flows between the respective devices and are therefore enabled by resilient ICT infrastructures [4]-[6].

III. CONTROL ARCHITECTURE

This section presents the architecture of the control system, and puts an emphasis on the choices taken to improve the resilience of the control system towards communication faults. The described control system only includes the low and medium voltage levels, however the complete architecture targeted in SmartC2net project can be found in [6].

A. Hierarchical Control Structure

A typical distribution grid operated by a DSO comprises of hundreds of primary substations and thousands of secondary substations each of these having hundreds of consumers. Thus, measures must be taken when designing the control system to get a manageable and controllable system. It is decided to adopt a hierarchical control structure for the targeted smart grid control applications. Figure 2 shows this control structure mainly consisting of two layers: Medium Voltage Level and Low Voltage Level. On each layer there is an associated controller and a collection of assets.

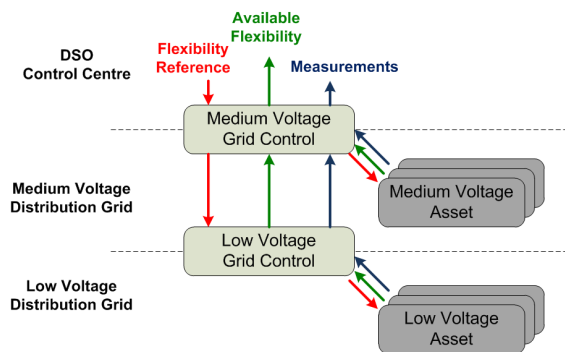


Figure 2. Hierarchical structure of the control system.

In terms of interfaces, the Medium Voltage Grid Controller (MVGC) receives a power set point from a higher hierarchical layer that is not in scope of the present work described in this paper, and sends back measurements of grid variables and available flexibility. The MVGC then controls its assets according to the received set-point. It is worth to

notice that the Low Voltage Grid Controller (LVGC) in this setup also acts as a flexible asset for the MVGC. Similarly, the LVGC controls its assets according to the set-point received from the MVGC, and sends back information on e.g. flexibility to the MVGC.

B. Control Functionalities and Requirements

The considered control system has two overall functionalities namely i) Tracking of power reference and ii) Voltage control.

The two functionalities are decoupled to allow different actors to operate them, as both functionalities may be relevant for DSO, while tracking of power reference may be relevant for an aggregation unit [8].

Finally, the control system must obey the physical constraints on e.g. cables in the grid in addition to regulatory constraints on the voltage magnitudes, which are specified in terms of 10 minutes mean values on each bus bar of the system [9].

C. Controllers

This section gives an overall description of the low and medium voltage controllers.

1) Low Voltage Grid Controller

The low voltage grid controller manages the usage of assets in the low voltage grid. These assets comprise batteries, PVs, EVs, and flexible households. Thus, the flexibility of the majority of these assets is stochastic. Furthermore, the communication between assets and controller is subject to delay and packet loss. To handle the variability in the number of available assets, the control system varies the set-points to the available assets such that the same dynamic behaviour is obtained irrespectively of the number of assets available, if this is possible within the constraints of the system. To handle the delay imposed by the communication, which may cause instability, the control system adapts its gains according to the delay, by decreasing the gain when the delay is increased. The cost of this is reduced bandwidth of the control system.

2) Medium Voltage Grid Controller

In this section an overview of the control system for energy balancing and loss minimization in the medium voltage grid is given. The controlled system consists of the electrical grid, flexible assets, e.g. wind and solar photovoltaics, and non-flexible loads. The control system structure is depicted in Figure 3.

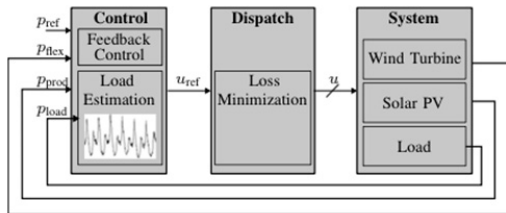


Figure 3. Control system structure.

It is seen from Figure 3 that this controller implements the functionalities *energy balancing* to follow the set-point p_{ref}

and *loss minimization* via a particular dispatch strategy. Note that the method is not limited to this particular set of assets, i.e., other assets may easily be added to the system. Based on estimation of inflexible load and the power reference signal p_{ref} , the feedback controller calculates a reference u_{ref} , which is dispatched to the flexible production units. Further, the medium voltage grid controller sees the low voltage grid controller as a flexible asset.

To estimate the non-flexible loads a linear model based on harmonic oscillators is used in combination with a Kalman filter. The result of applying this approach to 14 days of real residential consumption data is depicted in Figure 4.

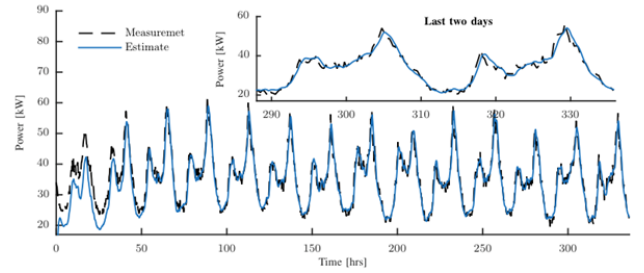


Figure 4. Performance of proposed estimation method throughout a 14-day period, evaluated on real consumption data.

The control signal, u_{ref} , produced by the control system detailed above, can be passed through a dispatch algorithm. The objective of the dispatch algorithm is to minimize active power loss while respecting asset constraints. By applying assumptions of no voltage issues, availability of voltage measurements, and estimation of active and reactive power at inflexible busses, the loss minimization problem can be shown to be convex. Thereby, it can be solved globally with known methods.

The voltage control functionality is based on safety verification techniques. It is said that a system is safe if it does not violate any constraints, and apply the barrier certificate method for proving the safety of this system [10]. This approach is illustrated through the simulation example shown in Figure 5 where the system clearly violates the voltage constraints if no curtailment algorithm is applied. This method not only guarantees that the constraints are not violated, but also at what voltage level it should be applied. It should be noted that this functionality can be applied on both a medium voltage and low voltage level.

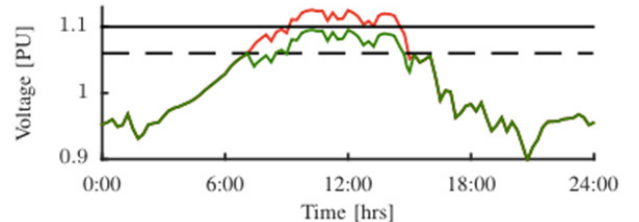


Figure 5. Voltage magnitude at the most critical bus, without any curtailment (red), and with curtailment (green). Curtailment is initiated when the voltage crosses the black dashed line.

I. REAL-TIME HIL SETUP

The second Use Case EGS in SmartC2net project as well as the control strategy presented above is supported by a Real-Time HIL setup that is developed at Aalborg University, Denmark [7].

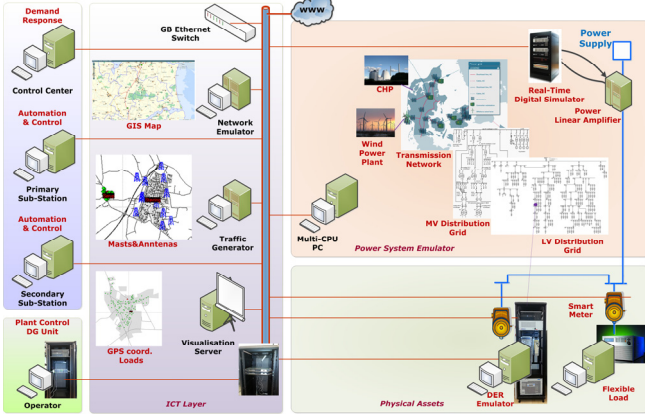


Figure 6. Architecture of Real-Time HIL setup [7].

The system comprise of several key elements as:

i) **Real-Time Power System Emulator.** This system comprises of two elements namely the Real-Time Digital Simulator and the Power Linear Amplifier. The Real-Time Digital Simulator based on Opal-RT is implementing a large scale energy network including systems using the multi-domain physics approach. This means that not only the electrical network and system is captured but also other systems such as thermal, mechanical, etc. The main goal for this Real-Time simulator is to capture the electrical system from the transmission level (TSO) down to low voltage distribution grids (DSO) as well as the district heating networks. Other energy systems such as gas networks and transportation systems can also be represented. The Opal-RT is able to simulate up to 20000 three-phase buses in RMS and 600 nodes EMT. Implementation of all models is based on MATLAB/Simulink. The 3-phase voltages measured in a given point in the distribution network are applied to the 50 kVA AC/DC fully regenerative Power Linear Amplifier that is supplying the physical components i.e. Dispersed Energy Resource, Flexible Load as they are part of the larger system. The three phase currents are fed in back to the Real-Time Digital Simulator.

ii) **Dispersed Energy Resource.** A fully regenerative four quadrant power converter is emulating the dispersed generation unit. It has $\pm 20\text{kW}/\pm 10\text{kVAR}$ capability and it is used to mimic characteristics of a small wind turbine, a PV systems or energy storage. Implementation of models as well as controls is done using MATLAB/Simulink on a dSpace 1103 system. This emulator is controllable remotely via the internal high-speed communication network.

iii) **Flexible Load.** A 4.5 kW Controllable AC/DC Load is used to mimic the behaviour of loads in a typical household. Implementation of models as well as controls is done using MATLAB/Simulink. This system is receiving set-points from hierarchical control structure.

iv) **Internal High-Speed Communication Network.** It is the ICT backbone for the setup and aims to emulate different technologies and topologies for the communication networks. A dedicated server is used to mimic the characteristics of different communication networks such as 3G, LTE, xDSL etc, for which all traffic between controllers and assets are routed through. A dedicated server is used for generating stochastic or trace-based background traffic patterns to emulate realistic cross traffic. This traffic is based on traffic models and traces of real network traffic. The network configuration includes mapping GIS data to communication network as well as Offline and Online network reconfiguration is done from a Visualization server. It is the purpose of the SmartC2Net project to develop an ICT platform that manipulates with the data access strategies in between entities (controllers and assets) to overcome potential issues in the network affecting the end to end QoS.

v) **Control Layers.** A dedicated platform for demand response is used to host functionalities related to aggregation and control of large scale flexible loads in distribution networks. A dedicated industrial controller (Medium Voltage Grid Controller) is used to host typical control functions in primary substations in medium voltage grids. It is also offering the possibility to implement and verify new control and operational strategies for components in medium voltage networks such as voltage control, loss minimization, etc. This industrial controller is getting information from the downstream assets placed in medium and low voltage networks as highlighted in the next sections of this paper. A dedicated industrial controller (Low Voltage Grid Controller) is used to host new control functionalities in secondary substations. This platform offers the possibility to implement and verify new control and operational strategies for flexible assets in low voltage networks such as voltage control along the low voltage feeders, aggregation of data from smart meters, etc. Another industrial controller is hosting typical control functionalities implemented in renewable based generation plants such as wind or PV. Implementation of controls in all platforms is done using MATLAB/Simulink.

vi) **Smart Meters.** Different smart meter technologies are providing power and energy consumption from the physical assets to the upper hierarchical control levels.

New components/actors can be easily added to this system.

II. EXPERIMENTAL RESULTS

A. Distribution Grid

A realistic medium voltage distribution grid with seven busses; two load busses, two production busses, and one bus managed by a local low voltage grid controller (LVGC) is considered to demonstrate the control strategy presented in Section III. The two non-controllable loads are aggregated residential loads and the two production units are a wind power plant (WPP) and a solar power plant (SPP). Realistic wind and irradiation profiles based on measured data are used for the system. The LVGC is managing a 41 bus residential grid with seven PV systems (yellow boxes), and three flexible assets (green boxes). The flexible assets are capable of both producing and consuming active and reactive power. This setup is depicted in Figure 7 and Figure 8. The medium

voltage grid controller (MVGC) receives measurements from the non-controllable loads as provided by Smart Meters, and information on current state and flexibility from the three assets (the MVGC sees the LVGC as a flexible asset). Based on an active power reference received from the upper layer and the aforementioned information, the MVGC distributes reference signals to the assets. The LVGC receives the reference signal from the MVGC and based on flexibility information on the low voltage level, distributes reference signals to the three fully controllable assets.

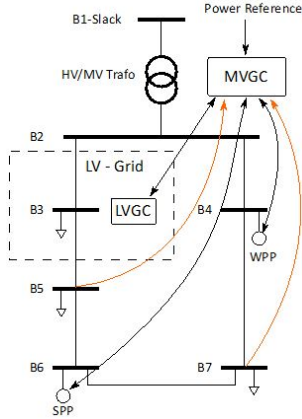


Figure 7. Layout of Medium Voltage Grid.

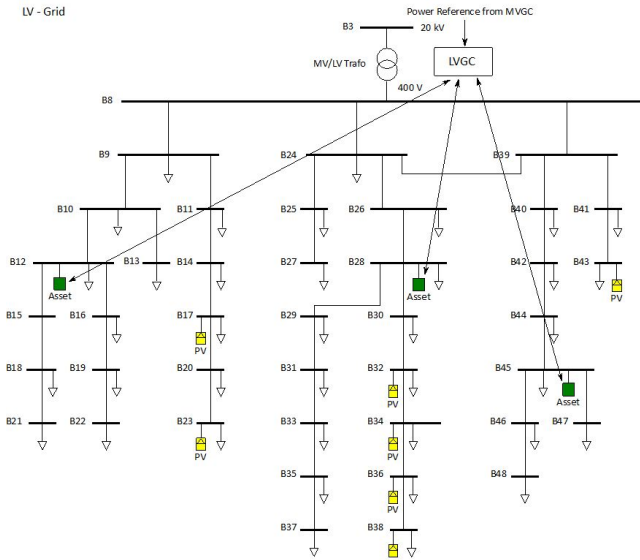


Figure 8. Structure of Low Voltage Grid.

All data traffic is routed through the network emulator and traffic generator servers. Packet loss and communication delays are obtained from real GPRS measurements and mapped on GIS data.

B. Simulation Results

The active power reference signal received by the MVGC has arbitrarily been chosen to illustrate the hierarchical control systems ability to follow a power reference. During six hours the reference is set to zero, which means that there is no

import or export from the high voltage grid and the entire MV/LV grid runs based on its own generation facilities.

The MVGC and LVGC's tracking ability is shown in Figure 9. The oscillations when a step in the reference is applied are caused by the communication delays present between the low voltage grid assets and LVGC. At 10:00 in the morning, the LVGC gains are adapted to handle the communication delays.

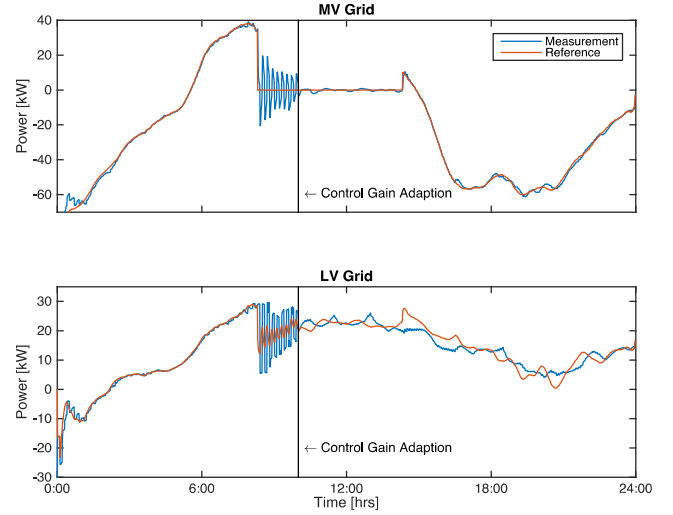


Figure 9. Tracking capability of the medium voltage grid controller (Top), and low voltage grid controller (bottom). Positive values indicate export and negative import of power.

The active power production of the SPP and WPP is illustrated in Figure 10 for the entire considered day.

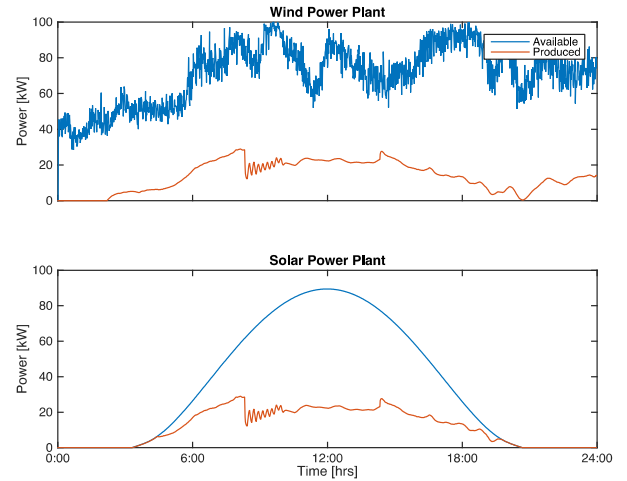


Figure 10. Production profiles of the wind power plant (Top), and the solar power plant (bottom).

Further, the active power injection/consumption of the low voltage grid assets is illustrated in Figure 11.

C. Discussion of Simulation Results

A number of interesting outcomes can be highlighted from the simulation results shown above. First, it is possible for both the MVGC and the LVGC to follow the references received closely up until the step in reference, which indicates

that via the hierarchical control structure it is possible for a distribution grid to offer services to upper hierarchical control layers. Secondly, when the step in reference occurs the measured power begins to oscillate heavily. This is caused by delay and loss in information between the LVGC and assets. However, when the control gains in the LVGC are adapted to handle the delay and loss, the oscillations settle and the system again follows the reference closely. The adaption in gain eliminates the oscillations but also decreases the reference following capability of the LVGC; which is expected as the bandwidth of the controller is decreased. This clearly illustrates the trade-off between robustness and performance in control. Moreover, the link between the communication network monitoring and the control algorithms is obvious, as the monitoring framework can deliver information of communication network state, to the controllers.

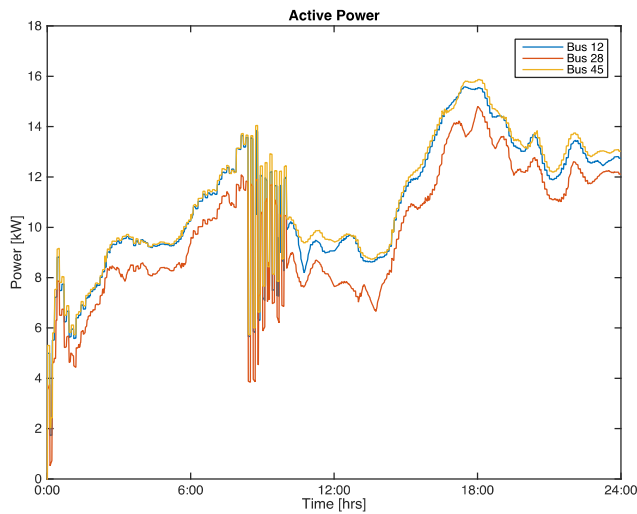


Figure 11. Power production from low voltage grid assets.

III. CONCLUSIONS

In this paper some of the key concepts of the EU FP7 project SmartC2Net are presented targeting the support of advanced smart grid controls when taking into account the communication networks. An overview on the required ICT architecture and its functionality is provided and a brief description of the External Generation Site use case including

control architectures is given. A key element in any smart grid applications is the evaluation and assessment of the developed solution accounting for real-time behaviour of the three main domains involved namely electrical grid, control layers and communication infrastructure. This paper is proposing a Real-Time HIL approach where all these elements are captured in a test bed. By doing this new Smart Grid control algorithms can be easily evaluated in a realistic manner and thus provide valuable information regarding boundaries of current communication technologies for specific control functionalities. Thus, the time-to-market can easily be reduced for advanced large scale Smart Grid controls.

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